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TECHNICAL NOTE

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VARIABLE-AMPLITUDE FATIGUE TESTS WITH PARTICULAR ATTENTION TO THE EFFECTS OF HIGH AND LOW LOADS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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VARIABLE-AMPLITUDE FATIGUE TESTS WITH PARTICULAR ATTENTION TO THE EFFECTS OF HIGH AND LOW LOADS

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SUMMARY

Variable-amplitude axial-load fatigue tests were conducted on 2024-T3 and 7075-T6 aluminum-alloy sheet specimens with a theoretical elastic-stress-concentration factor K_T of 4. The load schedules were designed to approximate gust-load statistics for tests on specimens of both alloys and maneuver-load statistics for tests on specimens of 7075-T6 aluminum alloy. The test data were analyzed by assuming linear cumulative damage, and a limited statistical analysis was used to strengthen conclusions. The value of the summation of cycle ratios $\sum \frac{n}{N}$ was found to vary with changes in frequency of application of the highest load level for eight-step tests and with the omission of the lowest load level for four-step tests. The variation in $\sum \frac{n}{N}$ was not significant when the lowest load level for eight-step tests was omitted.
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INTRODUCTION

Fatigue tests which are designed to represent anticipated service loadings have become increasingly important in recent years. Because the fatigue tests are often conducted on large components of new designs or on full-scale structures, time and cost are considerations of prime concern. The test designer must select the anticipated load history and in most cases reduce it to a small number of load levels which can reasonably be expected to give a realistic indication of the fatigue life. The reduction of a complex load history to a simple step test can introduce variations in fatigue life due to various testing techniques. Because of the prohibitive costs involved and the ad hoc nature of these fatigue tests, it has not been possible to determine which test techniques have a significant effect on fatigue life.

In order to help the test designer evaluate some of the suspected variables, the Langley Research Center has conducted an extensive program of variable-amplitude fatigue tests in which many systematic changes in the load program were made to determine their effect on the fatigue life of simple sheet specimens. Reference 1 presents the results of fatigue tests in which systematic variations were made in such parameters as sequence of loading, mean stress, and material for specimens tested by using loading schedules based on gust load statistics. Reference 2 presents results of tests in which load schedules based on statistics of maneuver load peaks were used. The block size and range of loads represented were systematically varied.

The present phase of the investigation is concerned primarily with the effect of the lowest load level in the test schedule. This level normally contains one-third or more of the load cycles to be applied in a test and, therefore, consumes a considerable portion of the testing time. Of secondary importance in this investigation is the influence of the number of load applications at the highest load level. In the present paper the results of additional variable-amplitude axial-load fatigue tests on 2024-T3 and 7075-T6 aluminum-alloy sheet specimens are combined with data presented in references 1 and 2 to ascertain whether omission of the lowest load level or changes in frequency of occurrence at the highest load level have an appreciable effect on fatigue life.

SYMBOLS

K_T	theoretical elastic stress-concentration factor
N	fatigue life, cycles
n	number of cycles applied at a given stress level
n_8	number of cycles at step eight of schedule
S_{alt}	alternating stress, ksi
S_d	stress at design limit load (43.6 ksi for 2024-T3 and 50.0 ksi for 7075-T6)
S_{mean}	mean stress, ksi
S_{min}	minimum stress, ksi
V_i	discrete gust velocity, fps

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SPECIMENS

Edge-notched sheet specimens of 2024-T3 and 7075-T6 aluminum alloy were used in this investigation. The edge notches gave a theoretical elastic stress-concentration factor K_T of 4. (See ref. 3.) This particular configuration was used because its fatigue behavior is reasonably close to the fatigue behavior of component parts (ref. 4) and is the same as the configuration used in references 1 and 2.

The specimens were made from part of a stock of commercial 0.090-inch-thick 2024-T3 and 7075-T6 aluminum-alloy sheets retained at the Langley Research Center for fatigue tests. Sheet layouts and material properties are given in references 5 and 6, respectively. The appropriate tensile properties are given in table I.

The specimen number identifies the specimen as to material, sheet number, and location within the sheet. For example, specimen A117N1-6 is 2024-T3 material (indicated by A) and was taken from the N1 position of sheet 117. The 6 indicates the position within the material blank (A117N1) from which the specimen blank was taken.

Specimen dimensions are shown in figure 1. The rolled surfaces were left as received and the longitudinal surfaces were machined and notched in both edges. The notch was formed by drilling a hole to form the notch radius. Residual machining stresses were minimized by first drilling with a small drill and then gradually increasing drill sizes (increment in diameter = 0.003 inch) until the proper radius was obtained. For consistency, drills were not used more than four times before being resharpened or replaced. The notch was completed by slotting with a 3/32-inch milling tool.

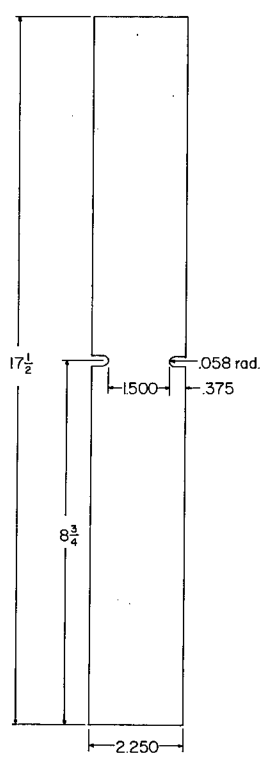

Figure 1.- Sheet-specimen details.

Burrs left in the machining process were removed by one of two methods. Although the effect of changing deburring processes was expected to be small, the same methods were used as had been used previously in order that the present data could be compared readily with existing data.

The first method (ref. 1) was used for specimens to be tested by using a load schedule based on gust load statistics and consisted of holding the specimen lightly against a rotating cone of 00 grade steel wool. The second method (ref. 2) was used for specimens to be tested by using load schedules designed to approximate a maneuver peak load history and consisted of holding the specimen lightly against a slowly rotating, pointed, bakelite dowel impregnated with a fine grinding compound. All specimens were inspected, and only those free of surface blemishes in and near the notch were tested.

MACHINES

All of the tests in this investigation were conducted in four axial-load fatigue machines (designated by numbers 6 to 9). Each of the machines is capable of two types of loading. One type of loading is mechanical, for which a beam is excited to vibrate near resonance by a rotating eccentric mass driven at 1,800 cpm by an electric motor. The vibrating beam imparts axial forces to the specimen which acts as one of the supports. (See fig. 2.) The other type of loading is hydraulic and uses the same basic machine structure. The hydraulic system includes a hydraulic ram, attachable to the lower specimen grip, an electrically driven hydraulic pump, a four-way solenoid valve, a semiautomatic electronic mechanism for load control, and a recorder for monitoring the loads. The mechanical drive system was used for low-amplitude cycles which occur very frequently, and the hydraulic system, with cycling rates up to 20 cpm, was used for the less frequent high-amplitude loads. A complete description of the hydraulic and mechanical systems is given in references 1 and 6, respectively.

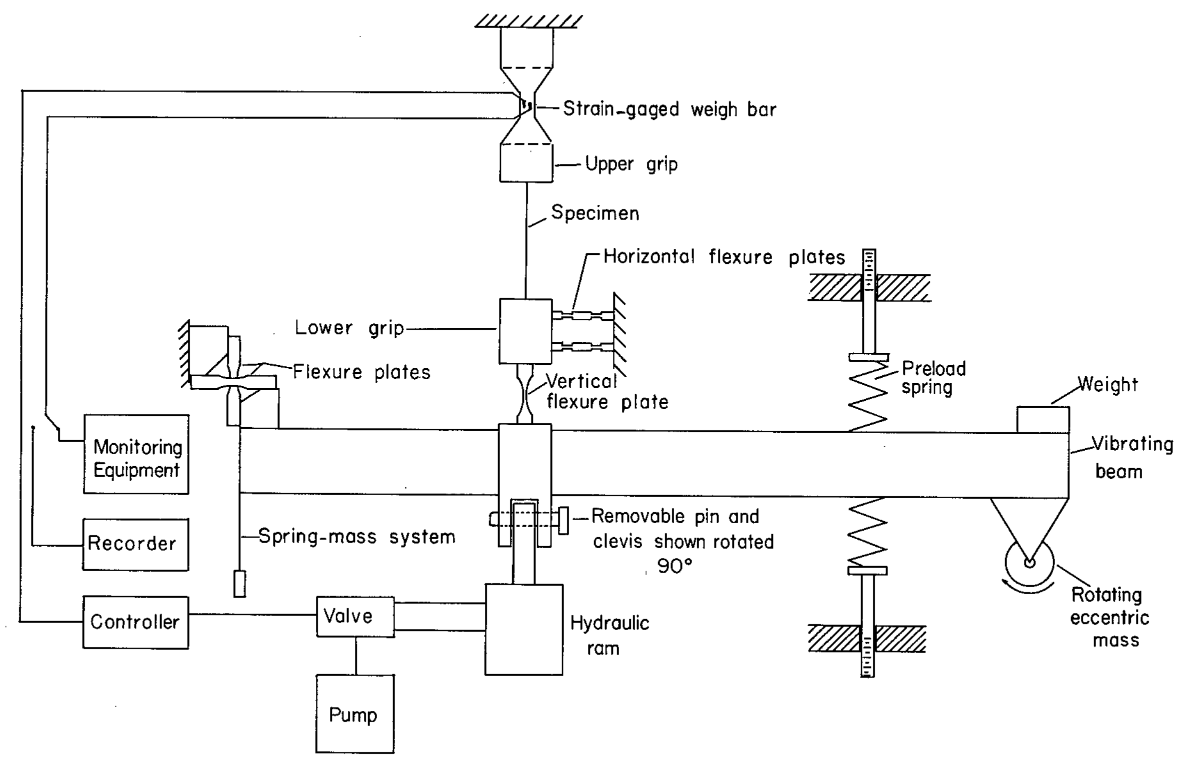

Figure 2.- Schematic diagram of fatigue testing machine.

The loads on the specimen were monitored by utilizing weigh bars, equipped with resistance wire strain gages, in series with the specimen. For mechanical loading, the strain-gage output was monitored by using an oscilloscope and associated balancing apparatus. The hydraulic system utilized the same strain-gage output to control the loads. The hydraulically applied loads were monitored on a strip-chart recorder with use of a second set of strain gages.

The load-measuring apparatus was calibrated periodically. The load on the specimen was estimated to be maintained within ±20 pounds of the desired load for the mechanical system and within ±50 pounds of the desired load for the hydraulic system.

LOADING SCHEDULES

Gust Loads

Eight-step loading schedules were used in this investigation to approximate a gust load history on the specimen. The load schedules used are taken from reference 1 and are presented in table II for 2024-T3 and 7075-T6 aluminum-alloy specimens. Statistical data on the frequency of occurrence of atmospheric gusts (ref. 7) were used as the basis for the loading schedules. For convenience, a shortened tabulation of the statistical values used is presented in the following table:

Gust velocity, ft/sec	Number exceeding
30	0.63
27.5	1.17
25	2.8
22.5	6.8
20	20
17.5	72
15	270
12.5	975
10	3,300
7.5	13,900
5	51,000
2.5	175,000
0	500,000

In order to convert these data to loading schedules, the following assumptions were made:

(1) A 30-fps gust produced design limit load

(2) Alternating stresses could be obtained from the following simple relation:

$$S_{alt} = \left(S_d - S_{mean}\right)\frac{V_i}{30}$$

With the use of the equation for alternating stress, the gust velocity spectrum was converted to a stress frequency spectrum for mean stresses of 17.4 ksi and 0 ksi for 2024-T3 and 20 ksi and 0 ksi for 7075-T6.

Each stress frequency spectrum was divided into eight approximately equal stress bands and a discrete stress level was selected to represent each stress band. The discrete stress level was determined by numerically integrating the theoretical damage for each stress band, linear damage accumulation being assumed, and then selecting a discrete value of stress that will produce the same damage in the same number of cycles. This process is explained in detail in reference 1. The integrating process required an S-N curve for each material and mean stress; data for these S-N curves are taken from references 1, 8, and 9 and are presented in figures 3 and 4. For stress bands which are lower than the fatigue limit (stress at which the fatigue life is 10^7 cycles) of the specimen, the discrete load level was selected at approximately the same relative position within the stress band as had been calculated for higher stress bands.

The summation of cycle ratios $\sum \frac{n}{N}$ where n is the number of cycles applied at a given stress level and N is the number of cycles to failure at the same stress level, for each test block was made to be approximately 0.1, so that failure would be expected to occur at the end of 10 test blocks. All stress cycles at a given level within a block were applied in one continuous sequence. The load levels within each block were applied in a random manner by using a sequence obtained from a table of random numbers. Each block had a different random schedule until the twentieth block; thereafter, the schedule for the first 20 blocks was repeated. The same random schedule was used for all tests.

Maneuver Loads

Eight- or four-step loading schedules based on the frequency of occurrence of peak loads in maneuvering flight were also used in this investigation. The load schedules used are taken from reference 2 and are presented in table III. Load statistics for the frequency of positive load factor peaks (ref. 10) were transformed into a peak stress frequency spectrum. This transformation required the following assumptions: (1) a design limit load factor of 7.3 and (2) a 1 g (level flight) stress equal to 7 ksi. The maneuver load statistics are presented in the following table:

Acceleration, g	Number exceeding
7.3	13
7.0	23
6.0	115
5.0	430
4.0	1,220
3.0	2,800
2.0	5,600
1.0	10,000

As in the case of gust loads the spectrum was divided into stress bands and a numerical integration of theoretical damage was performed to select discrete load

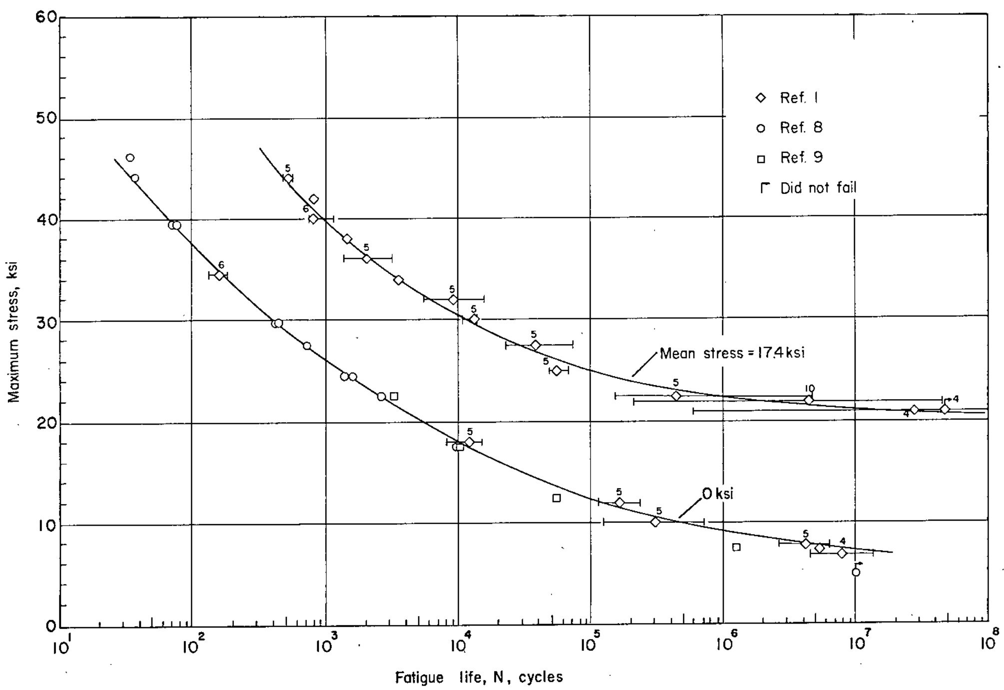

Figure 3.- Results of constant-amplitude fatigue tests of 2024-T3 aluminum-alloy specimens. (Ticks represent scatter bands and numerals indicate number of tests in each group.)

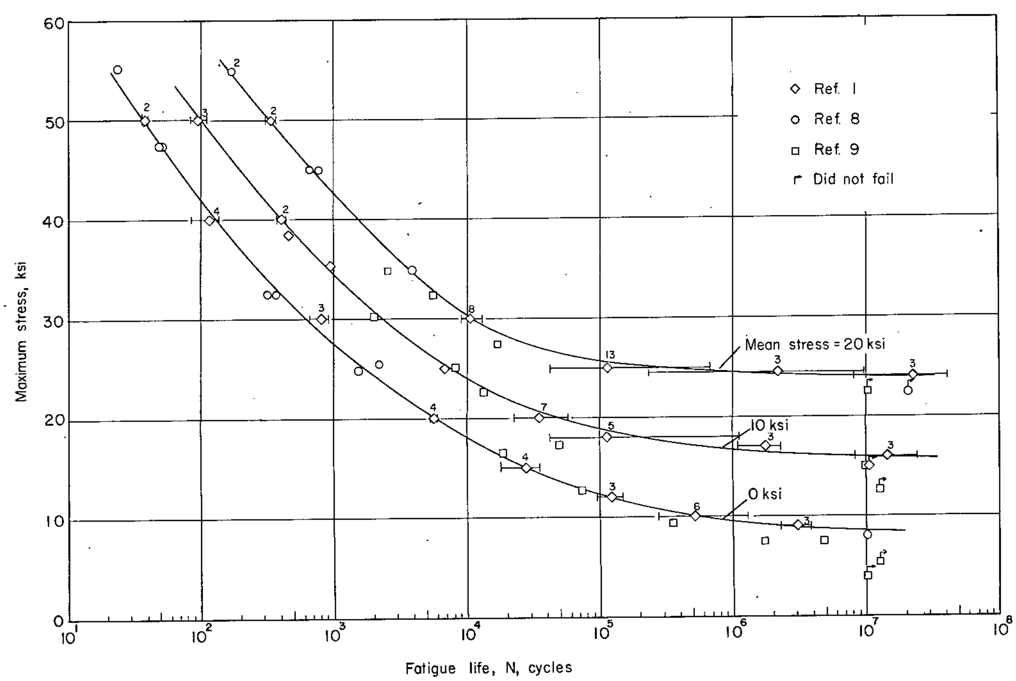

Figure 4.- Results of constant-amplitude fatigue tests of 7075-T6 aluminum-alloy specimens. (Ticks represent scatter bands and numerals indicate number of tests in each group.)

levels to represent each stress band. The S-N curve for maneuver loads required constant minimum stress rather than a constant mean stress as in the case of gust loads. This S-N curve is presented in figure 5 and is taken from reference 2. The same random sequence of loading used for the gust tests was used for these tests. Maneuver load tests were conducted on 7075-T6 specimens only. P9

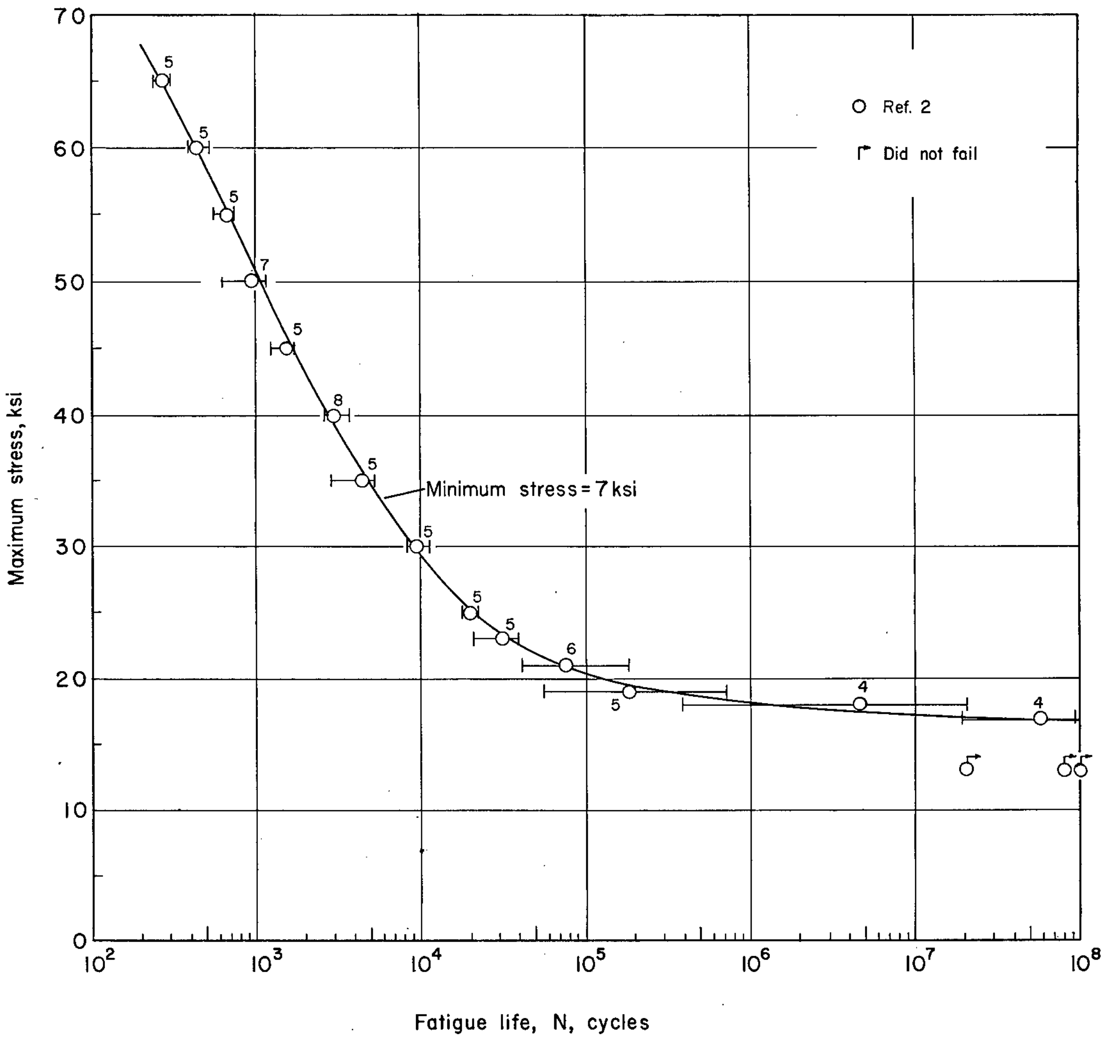

Figure 5.- Results of constant-amplitude fatigue tests of 7075-T6 aluminum-alloy specimens. (Ticks represent scatter bands and numerals indicate number of tests in each group.)

Test Variations

For each of the load schedules presented in tables II and III, a series of tests was conducted in which the lowest load level was omitted to determine whether this level had an effect on the fatigue life. Whether the lowest load level does or does not affect the fatigue life is important because the lowest load level contributes as many as 84 percent of the gust loads (33 percent for maneuver loads); thus, this load level materially influences testing time, and therefore, testing costs.

In addition, two series of tests were conducted with the lowest two load levels omitted (the higher of the two being above the fatigue limit) to determine whether the second lowest load level contributed an appreciable amount of damage.

The effect of changes in the highest load level was also investigated. The number of cycles n_8 at the highest load level was arbitrarily varied between 1 and 55 cycles per block for tests based on maneuver load statistics and from 1 cycle in 3 blocks to 1 cycle in 10 blocks for tests based on gust load statistics to study the possible effects of single or multiple periodically applied high loads. For tests in which the highest load level is applied less than once per block, the load was applied during the middle block of the span of blocks (that is, during blocks 5, 15, 25, etc., for tests having 1 cycle per 10 blocks).

RESULTS

Test Data

Test results are presented in tables IV to VI. Included in the tables and identified by the footnotes are data taken from references 1 and 2 which have been used with new data to establish whether the variations investigated have an effect on fatigue life. For completeness, tables IV to VI also contain the number of the machine in which the specimen was tested, the block and load step at failure, and the specimen life (total cycles).

Data Analysis

The results of these tests were compared on the basis of the values of $\sum \frac{n}{N}$ computed by the linear cumulative damage rule because of its simplicity and generally accepted usage. However, it should be noted that the same conclusions would have been obtained if specimen life (blocks to failure) had been compared.

The values of $\sum \frac{n}{N}$ for the variable-amplitude tests are given in tables IV to VI. In addition, the values of $\sum \frac{n}{N}$ are presented graphically in figure 6. In figure 6 the ticks represent the limits of scatter in data obtained from a group of tests conducted with the same load schedule. Each symbol represents the geometric mean of six tests.

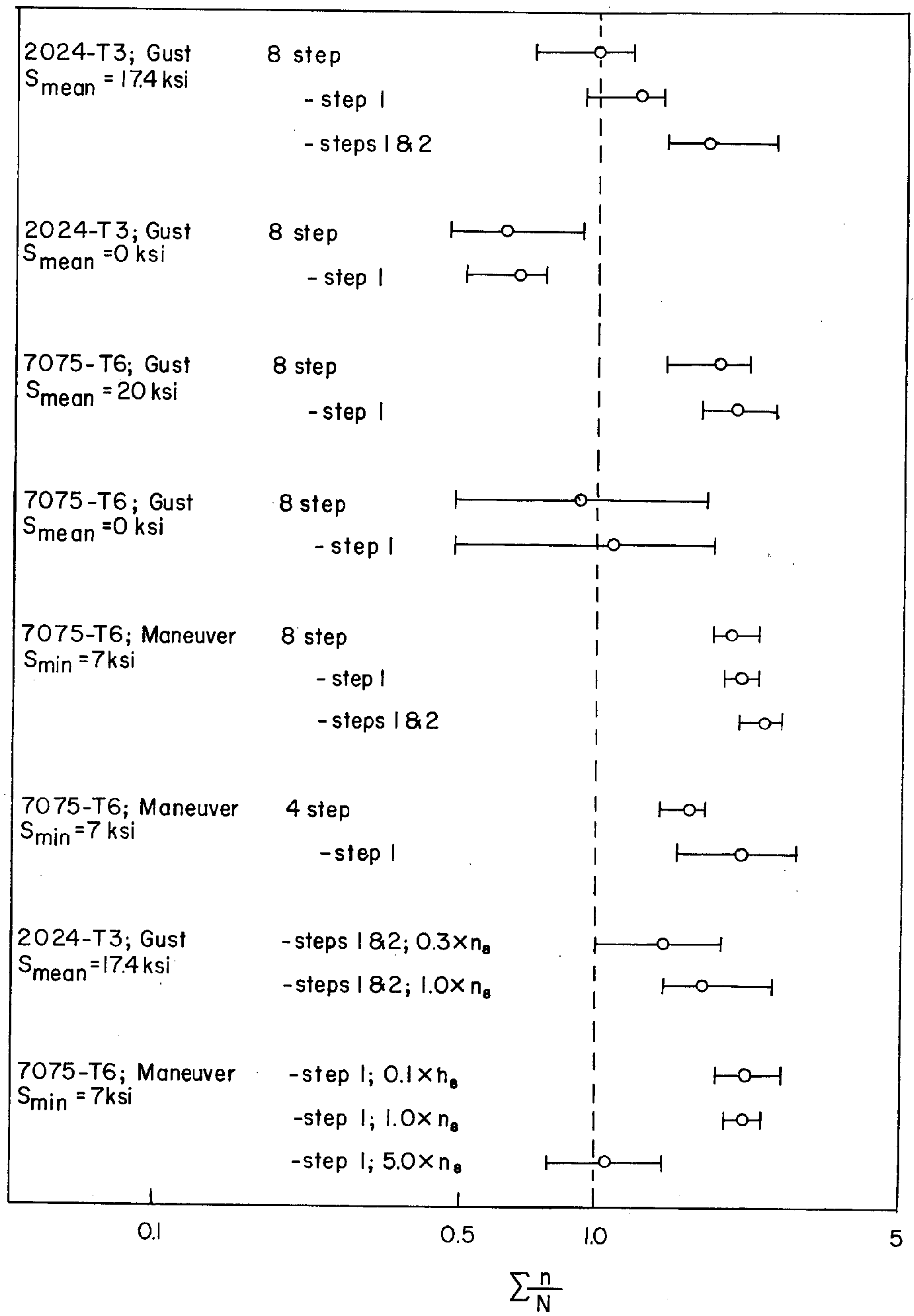

Figure 6.- Results of variable-amplitude fatigue tests of 2024-T3 and 7075-T6 aluminum-alloy specimens. (Ticks represent scatter bands; each symbol represents geometric mean of six tests.)

In order to establish more definitely whether an effect was present, the data were compared statistically, with reference 11 as a guide.[1] Two groups of tests differing in only one variable were used in each comparison. In order to make this statistical analysis, the distribution of $\sum \frac{n}{N}$ was assumed to be log normal and a 95-percent confidence level was used. The standard deviations of the logarithms of $\sum \frac{n}{N}$ were compared by the "F" test (i.e., sample standard deviations are (or are not) significantly different) and the means of the logarithms of $\sum \frac{n}{N}$ were compared by the "t" test (i.e., sample means are (or are not) significantly different). The results of the "t" tests and the ratio of the geometric means of $\sum \frac{n}{N}$ for each comparison of two test groups are presented in table VII.

DISCUSSION OF RESULTS

General

The scatter in these variable-amplitude fatigue tests is not considered excessive although the scatter approaches 2:1 for some test groups. (See fig. 6 and tables IV to VI.) The variation in $\sum \frac{n}{N}$ from test group to test group was also on the order of 2:1. Trends discernible in $\sum \frac{n}{N}$ due to the systematic variations in loading schedules are not predictable quantitatively and therefore require more detailed study. In subsequent sections of this paper, the aforementioned variations in $\sum \frac{n}{N}$ are qualitatively explained on the basis of residual stress and residual static strength considerations. A rather detailed explanation of these concepts is presented in reference 2; the following is a brief résumé of these explanations.

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[1]On page 44 of reference 11, $\beta = 1 - \alpha$ should be $\beta = 1 - \frac{\alpha}{2}$; therefore, in tables V and VIII of reference 11 values of $t_{0.975}$ and $F_{0,975}$, respectively, were used for the statistical analysis. β is the significance level and α is the preassigned significance level or chosen risk.

Damage and Failure Considerations

Residual stresses.- Residual stresses are obtained whenever the local stress at the base of a discontinuity exceeds the elastic limit of the material. Residual stresses are tensile for compression loads and compressive for tensile loads. The magnitude of the residual stress is not known although it is known that this value increases as the magnitude of the applied load increases.

The effect of residual stresses on fatigue life is very important. Compressive residual stresses developed in notched fatigue specimens delay fatigue crack initiation and propagation, thus improving fatigue life, whereas tensile residual stresses have the reverse effect. The incremental difference between the highest load level and successive load levels influences the rate at which the beneficial effect of the highest load level decays.

Residual static strength.- Failure of the specimen occurs when the applied load equals the residual static strength of the specimen. It is well known (see ref. 12) that the residual static strength of a specimen first decreases very rapidly as a crack is initiated and then deteriorates further with increasing crack length. Residual stresses seem to have very little, if any, effect on the residual static strength. High loads, which produce residual stresses that increase fatigue life by retarding crack initiation and propagation, may also cause early failure of a specimen containing a short fatigue crack if the load exceeds the specimen residual static strength.

Trends in fatigue life observed in the present tests are explained qualitatively on the basis of residual stress and residual static strength considerations.

Effect of Omitting the Lowest Load Level

The lowest load level contributes a large portion of the total load cycles and, thus, adds considerably to the testing time while contributing no theoretical damage ($n/N = 0$ since $N \to \infty$). For four-step tests, a value of n/N is given in table III for the lowest load level because the band represented includes stresses for which a portion of the S-N curve exists. However, the stress level used to simulate this stress band is less than the fatigue limit. In order to establish whether the lowest load level contributes an appreciable amount of actual damage, several series of tests were conducted for which the lowest load level was omitted.

Tests in which the lowest load level was omitted produced an increase in $\sum \frac{n}{N}$ over tests in which this level was included (see tables IV to VI and fig. 6), but this increase was found not to be significant (table VII) in five of the six comparisons made. The five comparisons of variation in $\sum \frac{n}{N}$ which were found not to be significant were for eight-step loading schedules covering a wide range of the possible combinations of material, mean stress, and load history. The one comparison in which the variation in $\sum \frac{n}{N}$ was found to be significant was for a four-step loading schedule.

From the preceding, the obvious conclusion would appear to be that the lowest load level in an eight-step loading schedule does not have a significant effect on fatigue life. Before deciding to omit the lowest load level, consideration should be given to the magnitude of the lowest load level and the number of load cycles at this level. This consideration is important because it is thought that the principal effect of the lowest load level is to contribute to the decay of the residual stress. However, it is possible that failure can occur at the lowest load level. (See ref. 1.) Failure can occur at the lowest load level only when the lowest load level is sufficient to propagate the fatigue crack; thus, the residual static strength is reduced to the value of the lowest load. It therefore seems reasonable that cycles of the lowest load can contribute damage especially after a fatigue crack has been initiated.

Effect of Omitting Two Low Load Levels

For two series of tests, the two lowest load levels were omitted to ascertain whether the second lowest load level has an important effect on the fatigue life. Tests in which the two lowest load levels were omitted produced an increase in $\sum \frac{n}{N}$ when compared with tests in which all of the load levels were applied and when compared with tests in which the lowest load level was omitted. (See tables IV to VI and fig. 6.) The increase in $\sum \frac{n}{N}$ was found to be significant for both comparisons. (See table VII.) An increase in life (blocks to failure) would be anticipated in tests in which the second lowest load level was omitted because any damage due to the second lowest load level would have to be contributed by other load levels; thus, additional cycles or blocks would be required. However, the observed increase in life was much larger than anticipated indicating that the actual damage due to the next to lowest load level is much greater than was calculated. Again, it is thought that the major influence of this load level is to contribute to the decay of beneficial residual stresses caused by higher loads and the data indicate that the influence is quite significant.

Effect of Varying the Frequency of Application of the Highest Load Level

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For three series of tests, the number of cycles n_8 at step eight of the schedule was multiplied by 0.1, 0.3, and 5.0, respectively, to determine whether the number of load applications at the highest load level had an effect on the fatigue life. In the interest of saving time, the two lowest loads were omitted in the tests simulating gust loads, and the lowest load level, in the tests simulating maneuver loads. This was assumed to be reasonable if the results of the tests were to be used qualitatively to establish trends. The lowest levels might influence the fatigue life (see previous two sections) but should have little effect on trends in life due to variations in the number of cycles at the highest load level.

For tests in which the highest load level was applied less than once per block (gust schedule, table II), a decrease in $\sum \frac{n}{N}$ would be anticipated if the beneficial effect of the highest load is reduced rapidly; thus, the residual stress due to a lower magnitude load would prevail during a large portion of the testing time. A comparison of $\sum \frac{n}{N}$ for tests in which the highest load level was applied once in three blocks or once in ten blocks indicates a decrease in $\sum \frac{n}{N}$ with a decrease in frequency of occurrence; however, the decrease in $\sum \frac{n}{N}$ was found not to be significant. (See tables IV and VII and fig. 6.)

For tests in which the highest load level is applied more than one time per block (maneuver schedule, table III), the value of $\sum \frac{n}{N}$ was found to decrease with an increase in the number of applications. (See table VI and fig. 6.) The statistical analysis indicates a significant difference (table VII) when the number of applications per block was increased from 11 to 55 but not when the number of applications was decreased from 11 to 1. The tendency for $\sum \frac{n}{N}$ to decrease as the number of cycles per block at the highest load level increased can be explained on premise of residual stresses. The magnitude of the highest load is not changed; therefore, the magnitude of the residual stress due to the first application of the highest load should not change. However, as the highest load is applied more than one time, each additional cycle produces damage at an increasing rate. When large numbers of the highest load level are applied, the latter cycles probably produce damage at a reasonably fast rate.

Other Observations

Several of the trends previously noted in references 1 and 2 were also noted in the tests which were run in this investigation. The ones of interest are noted as follows:

(1) The value of $\sum \frac{n}{N}$ increases as the mean stress increases. (See ref. 1.) This effect has been noted by many observers and has been attributed to the formation of beneficial residual stresses as the mean stress is increased.

(2) The value of $\sum \frac{n}{N}$ tends to be higher for tests of 7075-T6 aluminum alloy than for 2024-T3 aluminum alloy. (See ref. 1.) The reason for this is not known.

(3) The load step at failure was found to have trends similar to those reported in references 1 and 2. That is, for tests simulating gust loads in which the mean stress was zero, the specimen tended to fail at the high loads; whereas, for tests in which the mean stress was positive, the tendency was for failure at the lower loads. (See ref. 1.) All maneuver load tests resulted in failure at the highest load level which is in agreement with results reported in reference 2. The reason for the pattern of failure loads in the gust load tests is not known. It is reasonable to explain the failures at high load levels in the case of maneuver load tests by the increased number of high-load cycles, which presents ample opportunity for a fatigue crack to propagate and for the residual static strength to be exceeded.

CONCLUDING REMARKS

Variable-amplitude axial-load fatigue tests of 2024-T3 and 7075-T6 aluminum-alloy specimens were conducted according to loading schedules designed to approximate either gust load or maneuver peak load histories with and without arbitrary modifications.

For tests having eight load levels, omitting the lowest load level did not produce a significant change in the summation of cycle ratios $\sum \frac{n}{N}$ although the tests without the lowest load level had consistently higher values of $\sum \frac{n}{N}$. For four-load-level tests, the value of $\sum \frac{n}{N}$ increased significantly when the lowest load level was omitted. Caution should therefore be used in deciding whether or not to omit the lowest load level.

For tests in which the two lowest load levels were omitted, the sharp increase in $\sum \frac{n}{N}$ was significant when compared with tests in which only the lowest load level was omitted and with tests in which all levels were included.

The increase in life (blocks to failure) was much greater than would be expected on the basis of linear cumulative damage; this result indicates that the damage due to the next to lowest load level is much greater than that calculated.

The number of cycles at the highest load level was varied for two types of tests; one type had more than one cycle of the highest load level per block (maneuver peak history), and one type had less than one cycle of the highest load level per block (gust history). The trend seems to be for $\sum \frac{n}{N}$ to be maximum when the highest load level is applied one time per block; thus, maximum beneficial residual stresses are produced without introducing appreciable damage.

Trends in $\sum \frac{n}{N}$ noted in previous investigations and also observed in this investigation are:

(a) The value of $\sum \frac{n}{N}$ tended to be greater than 1 for tests with a positive mean stress and 1 or less for tests with zero mean stress.

(b) The value of $\sum \frac{n}{N}$ tended to be higher for tests of 7075-T6 aluminum alloy than for 2024-T3 aluminum alloy.

(c) Specimens tended to fail at the high load levels for tests simulating a maneuver peak history or a gust load history with a zero mean stress.

(d) For tests simulating gust loads with a positive mean stress, specimens tended to fail at the lower load levels.

The phenomena of residual stresses and residual static strength are thought to qualitatively explain the trends noted. end

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 28, 1962.

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TABLE I.- TENSILE PROPERTIES OF ALUMINUM-ALLOY MATERIALS TESTED

[Data from ref. 6]

	Average	Minimum	Maximum
7075-T6 (152 tests):			
Yield stress (0.2-percent offset), ksi	75.50	71.54	79.79
Ultimate tensile strength, ksi	82.94	79.84	84.54
Total elongation (2-inch gage length), percent	12.3	7.0	15.0
2024-T3 (147 tests):			
Yield stress (0.2-percent offset), ksi	52.05	46.88	59.28
Ultimate tensile strength, ksi	72.14	70.27	73.44
Total elongation (2-inch gage length), percent	21.6	15.0	25.0

TABLE II.- VARIABLE-AMPLITUDE LOADING SCHEDULES;

GUST LOADS*

Step	Representative stress, ksi	n	n/N Step	Step	Representative stress, ksi	n	n/N Step
2024-T3 aluminum-alloy specimens							
S_{mean} = 17.4 ksi				S_{mean} = 0 ksi			
1	2.1	82,000	0	1	2.2	41,000	0
2	5.1	15,000	.016660	2	8.0	7,850	.001869
3	8.2	2,800	.038360	3	13.2	980	.019600
4	11.3	350	.018940	4	18.5	143	.014300
5	14.5	46	.007080	5	23.8	23	.012105
6	17.7	7.4	.002680	6	29.2	3	.008824
7	21.0	1.6	.001208	7	34.8	.73	.004294
8	24.1	.35	.000466	8	40.4	.11	.001896
		$\sum \approx$ 100,205	$\sum$ 0.085394			$\sum \approx$ 50,000	$\sum$ 0.062888
7075-T6 aluminum-alloy specimens							
S_{mean} = 20.0 ksi				S_{mean} = 0 ksi			
1	1.5	42,000	0	1	3.8	24,400	0
2	5.3	7,500	.046875	2	9.1	4,800	.002087
3	8.7	1,190	.071687	3	15.0	690	.025091
4	12.6	175	.030172	4	21.2	98	.023333
5	16.3	23	.007931	5	27.2	14	.007778
6	20.1	2.5	.001678	6	33.7	1.8	.005625
7	23.9	.5	.000610	7	39.9	.33	.002538
8	27.5	.1	.000208	8	46.3	.074	.001276
		$\sum \approx$ 50,900	$\sum$ 0.159161			$\sum \approx$ 30,000	$\sum$ 0.067728

*Data from reference 1.

TABLE III.- VARIABLE-AMPLITUDE LOADING SCHEDULES

FOR 7075-T6 ALUMINUM-ALLOY SPECIMENS;

MANEUVER LOADS*

$[S_{min} = 7.0 \text{ ksi}]$

Step	Representative stress, ksi	n	$\frac{n/N}{\text{Step}}$
Eight-step tests			
1	2.8	1,030	0
2	8.3	780	.000050
3	13.8	510	.006806
4	19.2	300	.018745
5	24.7	180	.025297
6	30.0	88	.023588
7	35.3	35	.016417
8	41.8	11.5	.009070
		$\sum \approx 2,935$	$\sum$ 0.099973
Four-step tests			
1	5.5	1,810	0.000050
2	16.0	810	.024000
3	26.5	263	.047017
4	37.0	46.5	.024538
		$\sum \approx 2,935$	$\sum$ 0.095605

*Data from reference 2.

TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE AXIAL-LOAD FATIGUE TESTS

ON 2024-T3 ALUMINUM-ALLOY SPECIMENS; GUST LOADS

(a) S_{mean} = 17.4 ksi; eight-step tests

Specimen	Machine	Failure		Life, cycles	$\sum \frac{n}{N}$
		Block	Step		
Eight steps					
*A111N1-6	8	15	7	1,402,940	1.20
*A111N1-1	9	14	5	1,402,840	1.19
A36N2-9	6	13	4	1,302,400	1.09
*A111N1-7	8	13	7	1,202,470	1.03
A36N2-10	8	11	4	1,084,460	.88
*A115N1-2	9	10	3	903,240	.72
Geometric mean				1,200,000	1.00
Step 1 omitted					
A36N2-8	7	17	7	306,700	1.41
A120N1-2	6	17	7	306,700	1.41
A118N1-10	9	16	6	288,480	1.32
A27N2-2	9	16	6	288,470	1.32
A114N1-3	6	13	4	236,440	1.09
A113N1-5	8	12	4	200,260	.94
Geometric mean				268,000	1.24
Steps 1 and 2 omitted; cycles for step 8 = 1.0 × n_8					
A28N2-3	6	38	3	120,280	2.56
A118N1-9	7	31	6	106,210	2.09
A28N2-5	7	25	5	79,780	1.70
A121N1-1	9	25	3	78,330	1.67
A119N1-3	6	22	4	67,510	1.46
A28N2-1	6	21	5	67,270	1.44
Geometric mean				84,450	1.78
Steps 1 and 2 omitted; cycles for step 8 = 0.3 × n_8					
A30N2-1	7	29	7	89,750	1.92
A26N2-4	7	28	4	89,650	1.91
A33N2-1	7	22	3	69,660	1.49
A37N2-5	6	22	3	69,660	1.49
A37N2-4	7	16	5	48,470	1.05
A37N2-6	7	15	8	47,720	1.00
Geometric mean				67,040	1.43

(b) S_{mean} = 0 ksi; eight-step tests

Specimen	Machine	Failure		Life, cycles	$\sum \frac{n}{N}$
		Block	Step		
Eight steps					
*A120N1-7	9	15	8	742,000	0.93
*A121N1-4	9	12	7	551,120	.73
*A121N1-3	8	10	7	458,990	.61
*A117N1-4	8	10	7	458,990	.61
*A122N1-9	9	8	5	399,990	.49
*A120N1-9	9	8	6	349,580	.47
Geometric mean				478,600	0.62
Step 1 omitted					
A117N1-6	9	13	6	108,000	0.76
A121N1-5	6	12	7	100,200	.73
A118N1-5	9	12	7	100,200	.73
A120N1-5	9	10	6	90,000	.63
A122N1-6	6	10	7	90,000	.63
A120N1-6	6	8	5	72,000	.50
Geometric mean				92,600	0.66

*Published in reference 1.

TABLE V.- RESULTS OF VARIABLE-AMPLITUDE AXIAL-LOAD FATIGUE TESTS ON 7075-T6 ALUMINUM-ALLOY SPECIMENS; GUST LOADS

(a) S_{mean} = 20 ksi; eight-step tests

Specimen	Machine	Failure		Life, cycles	$\sum \frac{n}{N}$
		Block	Step		
Eight steps					
*B28N1-8	7	14	2	712,450	2.22
*B26N1-1	6	14	5	712,440	2.22
B103N1-7	7	13	3	660,340	1.96
B103N1-5	6	13	1	643,130	1.96
*B43N1-7	8	12	3	558,810	1.75
*B43N1-9	9	10	3	458,020	1.43
Geometric mean				617,000	1.90
Step 1 omitted					
B110N1-1	6	16	3	142,120	2.54
B103N1-9	7	15	8	125,690	2.36
B110N1-2	6	14	2	121,450	2.20
B103N1-3	7	13	3	114,450	1.98
B103N1-2	8	12	7	99,170	1.85
B101N1-2	6	11	3	97,380	1.71
Geometric mean				115,700	2.09

(b) S_{mean} = 0 ksi; eight-step tests

Specimen	Machine	Failure		Life, cycles	$\sum \frac{n}{N}$
		Block	Step		
Eight steps*					
B44N1-9	9	26	7	775,310	1.73
B43N1-5	9	18	7	540,110	1.22
B28N1-6	6	14	7	398,150	.91
B43N1-1	8	12	7	330,830	.80
B43N1-6	8	12	7	330,830	.80
B43N1-3	8	7	8	210,010	.47
Geometric mean				393,900	0.91
Step 1 omitted					
B103N1-10	6	27	7	150,610	1.79
B110N1-8	6	20	8	106,480	1.30
B110N1-7	7	20	8	106,480	1.30
B110N1-10	6	19	6	105,790	1.26
B83N2-4	7	15	7	87,470	.96
B103N1-1	7	7	8	39,210	.47
Geometric mean				92,300	1.09

*Published in reference 1.

TABLE VI.- RESULTS OF VARIABLE-AMPLITUDE AXIAL-LOAD FATIGUE TESTS

ON 7075-T6 ALUMINUM-ALLOY SPECIMENS; MANEUVER LOADS

[S_{min} = 7.0 ksi]

(a) Eight-step tests

Specimen	Machine	Failure		Life, cycles	$\sum \frac{n}{N}$
		Block	Step		
Eight steps*					
B52N1-4	8	24	8	69,911	2.34
B95N1-2	7	23	8	64,694	2.23
B51N1-2	6	21	8	59,815	2.04
B50N1-9	8	20	8	55,766	1.91
B56N1-1	6	19	8	54,083	1.85
B50N1-5	6	19	8	54,082	1.85
Geometric mean				59,440	2.02
Step 1 omitted; cycles for step 8 = 1.0 × n_8 *					
B91N1-8	7	24	8	45,186	2.34
B129S1-1	7	24	8	45,182	2.34
B91N1-7	8	22	8	40,032	2.12
B128S1-2	8	22	8	40,031	2.12
B52N1-10	8	22	8	40,031	2.12
B91N1-3	7	21	8	39,110	1.96
Geometric mean				41,520	2.16
Steps 1 and 2 omitted					
B102N1-1	6	27	8	30,088	2.63
B102N1-9	9	27	8	30,088	2.62
B107N1-9	6	26	8	29,226	2.59
B109N1-2	9	25	8	27,509	2.41
B107N1-6	6	23	8	24,828	2.22
B107N1-8	9	22	8	23,650	2.12
Geometric mean				27,670	2.42
Step 1 omitted; cycles for step 8 = 0.1 × n_8					
B102N1-4	6	30	8	54,930	2.66
B108N1-4	9	25	7	47,053	2.27
B102N1-7	6	24	8	44,944	2.14
B108N1-6	9	24	8	44,943	2.14
B105N2-6	9	22	8	39,812	1.94
B107N1-4	6	21	8	38,997	1.87
Geometric mean				44,810	2.19
Step 1 omitted; cycles for step 8 = 5.0 × n_8					
B107N1-3	6	11	8	20,094	1.44
B108N1-3	9	11	8	20,086	1.43
B107N1-2	6	10	8	17,545	1.22
B108N1-7	9	9	8	15,915	1.12
B108N1-9	9	7	8	13,346	.87
B108N1-8	9	6	8	10,883	.79
Geometric mean				15,930	1.07

(b) Four-step tests

Specimen	Machine	Failure		Life, cycles	$\sum \frac{n}{N}$
		Block	Step		
Four steps*					
B97N1-3	8	19	4	54,819	1.78
B97N1-5	7	18	4	52,727	1.72
B96N1-9	8	18	4	52,699	1.70
B96N1-4	8	18	4	52,687	1.70
B96N1-2	7	17	4	46,894	1.54
B97N1-2	9	15	4	43,889	1.41
Geometric mean				50,470	1.64
Step 1 omitted*					
B107N1-7	9	30	4	33,732	2.87
B107N1-5	9	27	4	30,085	2.53
B102N1-3	6	24	4	26,943	2.27
B102N1-8	6	23	4	24,765	2.10
B102N1-2	6	20	4	21,634	1.86
B107N1-1	9	17	4	18,028	1.55
Geometric mean				25,330	2.15

*Published in reference 2.

TABLE VII.- RESULTS OF STATISTICAL ANALYSIS OF VARIABLE-AMPLITUDE FATIGUE TESTS

Load history	Gust								Maneuver				Gust			Maneuver			Gust		Maneuver			
Material	2024-T3				7075-T6				7075-T6				2024-T3			7075-T6			2024-T3		7075-T6			
Mean stress	17.4		0		20		0		S_{min} = 7 ksi				17.4			S_{min} = 7 ksi			17.4		S_{min} = 7 ksi			
Side group (Load history, Material, Mean stress, Condition) / Top group (Condition)	8 step	- step 1	8 step	- step 1	8 step	- step 1	8 step	- step 1	8 step	- step 1	4 step	- step 1	8 step	- step 1	- steps 1 and 2	8 step	- step 1	- steps 1 and 2	8 step - steps 1 and 2	- steps 1 and 2 0.3 × n_8	8 step	- step 1 0.1 × n_8	- step 1 1 × n_8	- step 1 5 × n_8
Gust, 2024-T3, 17.4, 8 step		No																						
Gust, 2024-T3, 17.4, - step 1	0.81																							
Gust, 2024-T3, 0, 8 step				No																				
Gust, 2024-T3, 0, - step 1			0.95																					
Gust, 7075-T6, 20, 8 step						No																		
Gust, 7075-T6, 20, - step 1					0.91																			
Gust, 7075-T6, 0, 8 step								No																
Gust, 7075-T6, 0, - step 1							0.88																	
Maneuver, 7075-T6, S_{min} = 7 ksi, 8 step										No														
Maneuver, 7075-T6, S_{min} = 7 ksi, - step 1									0.94															
Maneuver, 7075-T6, S_{min} = 7 ksi, 4 step												Yes												
Maneuver, 7075-T6, S_{min} = 7 ksi, - step 1											0.76													
Gust, 2024-T3, 17.4, 8 step														No	Yes									
Gust, 2024-T3, 17.4, - step 1													0.81		Yes									
Gust, 2024-T3, 17.4, - steps 1 and 2													0.56	0.69										
Maneuver, 7075-T6, S_{min} = 7 ksi, 8 step																	No	Yes						
Maneuver, 7075-T6, S_{min} = 7 ksi, - step 1																0.94		Yes						
Maneuver, 7075-T6, S_{min} = 7 ksi, - steps 1 and 2																0.83	0.89							
Gust, 2024-T3, 17.4, 8 step - steps 1 and 2																				No				
Gust, 2024-T3, 17.4, - steps 1 and 2 0.3 × n_8																			1.24					
Maneuver, 7075-T6, S_{min} = 7 ksi, 8 step																						No	No	Yes
Maneuver, 7075-T6, S_{min} = 7 ksi, - step 1 0.1 × n_8																					0.93		No	Yes
Maneuver, 7075-T6, S_{min} = 7 ksi, - step 1 1 × n_8																					0.94	1.01		Yes
Maneuver, 7075-T6, S_{min} = 7 ksi, - step 1 5 × n_8																					1.89	2.04	2.02	

No	Sample $\sum \frac{n}{N}$ geometric means are not significantly different
0.93	Ratio of sample $\sum \frac{n}{N}$ geometric means, $\frac{\text{Top group}}{\text{Side group}}$

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